Electric Discharge Machining of Titanium and Alloys for Biomedical Implant Applications: A Review

Vijay Kumar[1*], Naveen Beri[2] & Anil Kumar[3]

[1*]Research Scholar, Inder Kumar Gujral Punjab Technical University, Kapurthala, Punjab, India,Pin Code: 144601
[2,3]Department of Mechanical Engg. Beant College of Engineering & Technology, Gurdaspur, Punjab, India.

Received: May 10, 2018 Accepted: June 17, 2018

ABSTRACT *Electrical discharge machining (EDM) is an advanced machining process among newly developed non-traditional machining processes for Surface Machining of rigid materials, especially super alloys and biomaterials. The diverse material electrodes have given an alternative tooling option to the researchers to increase surface quality of materials. Investigators and scientists have found numerous electrodes during electric discharge machining of various types of bio-materials. Titanium alloy remains the material of choice for the medical and dental industry for implants, pacemakers, as well as hip and knee replacements. The different techniques used for experimental design and analysis techniques have been implemented to understand the effects, contribution, significance and optimal machine settings of process parameters, namely, polarity, peak current, electrode type, pulse on time and gap voltage on material removal rate, tool wear rate, surface roughness and wear ratio. This review paper clearly exhibits the detailed study of parameters that critically influence the machinability and the optimal combination levels of machining parameters for MRR, TWR, SR and WR. It is clear that different type of electrodes gives different results like MRR, TWR, SR and WR in machinability of bio-materials. This paper also illustrates the key problems and adequate results for future investigation.*

Keywords: *Titanium, alloy, biocompatibility, surface modification, Implant, electric discharge machining.*

Introduction

The rigid materials and super alloys hold prominent role in world's top engineering fields namely Aerospace, Marine, chemical industries and Biomedical applications. Rigid materials and super alloys are basically high performance materials and alloys having excellent chemical, physical, thermal and biological properties. A vast study is required to understand and to discover most prominent materials for their respective functionality in the Engineering and biomedical field. Number of researchers and scientists from all over the globe are continuously working on material compositions and alloys to introduce best materials and alloys having suitable chemical, physical and biological properties required to execute cost efficient, quality manufacturing and Bio-compatibility techniques. After the discovery of Titanium, Aluminium, vanadium and Magnesium based rigid materials and alloys, the recent researches are fully concentrated on the machinability of these alloys to improve the quality and usage parameters.

The Electro-Discharge Machining technique is most adequate Material removal technique for rigid materials and alloys. The EDM is the machining process acquired to remove the material and to produce a desired surface and shape of a particular material and alloy using electrical discharge.

EDM machining techniques was firstly discovered by an English scientist Joseph Priestley in 1770s. In 1930s, Scientists machined the material by using Electrical discharges for the first time. The intermittent arc discharges caused erosion that was occurred in air between the tool electrode and work piece. Electric discharge machining was when Russian scientists later in 1943 during World War II, Lazarenko&Lazarenko, two Russian Scientists learned to control the erosive effect and to use it for machining purposes. To keep control of pulse time and to hold gap between work piece and electrode, the resistance-capacitance relaxation circuit was introduced in 1950s and then commercially developed in 1970s.

In 1980s, EDM achieved its tremendous advancement after the integration with Computer numerical control (CNC) and improved the efficiency of machining operations. After then, CNC enabled EDM started to be opted for machining of geometrically complex and rigid materials. EDM is now playing its vital role in die and mold making industries, nuclear industries, aerospace, aeronautics and biomedical industries Today, EDM has replaced traditional machining operations like drilling and milling with Lathe machine and is now a well-established machining option in many manufacturing industries throughout the world.

Human Body and Titanium Alloy

The human body is the combination of numerous organic and inorganic substances. Bones are the fundamental component of human body as Collagen and Hydroxyapatite present in bone provide strength, flexibility and shape to the body [1,2]. Bones are basically consists Ca, Mg and Potassium along with electrolytes. It is observed that Accidents, aging or diseases are the main reasons for the bone failure and lead to biomedical implants to cover the restrictions due to bone fracture [3-5].

Although Human body doesn't accepts the foreign substances completely except edible substances, but it is observed that Titanium is result of Benchmark discovery to be used in various compositions as titanium alloy for medical implants. Titanium forms stable oxide layer on the surface thus exhibiting excellent Biocompatibility required for a human body for growth and Titanium Alloy Ti-6Al-4V is preferred as the most common super alloy used for biomedical implants [6-8].

The surface of titanium alloy namely Ti-6Al-4V exhibits several positive as well as negative influences like toxicity of chemical substances present in it as per as Medical implant is concerned [9]. Thus a vast study is required to understand the Titanium alloy by knowing its mechanical, physical and chemical properties. Electric discharge Machining plays a vital role in manufacturing biomaterials and artificial body parts as it is opted for surface roughness of hard materials and implant alloys like Ti-6AL-4V.

Electric Discharge Machining ofTitanium Alloy

When Aluminium and Vanadium based titanium alloy Ti-6AL-4V is machined using Electric Discharge machining, it provide notable surface finish required for further use in Biomaterials or Aerospace parts. Scientists and researchers are continuously working on the surface stability and other properties of this alloy with different methodologies and techniques. It is seen that every methodology has a different influence on titanium alloy as discussed in the review study. It has been seen that Ti-6AL-4V depicts different properties due to surface treatment when investigators used high peak current in EDM machining to investigate tensile and surface roughness. The peak current of different values is used and chemical changes are studied with the help of X-ray analyzer. It reflects that EDM machined samples are preferable substances for MG-63 cells of human osteoblast as per adhesion and growth is concerned [10].

Dielectric has vital role in machining operation in Micro Electro discharge machining (also Called as Micro-EDM). Machining characteristics are impacted by the nature of dielectric. Numerous Research investigations address the issues of micro-EDM utilizing different types of kerosene and deionized water to explore the influence of the dielectrics on the performance criteria such as material removal rate, tool wear rate, overcut, material variance at entry and exit hole and surface integrity during machining of titanium alloy (Ti-6AI-4V) [11]. As seen in various investigations, the Material removal rate and TWR higher with Deionized water as compared to Kerosene. It is also observed that when suspended particles were used along with dielectric, MMR is increased with Deionized water but Tool wear rate (TWR) is decreased by using Kerosene as Dielectric. From the micrographs taken from the scanning electron Microscope (SEM) it has also observed that Deionized water based EDM has the lesser thickness of white layer on machined surface as compared to Kerosene oil. In addition to this, machining time is also studied by using four different dielectrics having different properties and with different machining parametric settings respectively. In addition to it, Machine surface integrity and Wear occurred on micro tool is also checked for every dielectric respectively with the help of SEM microscope. Thus, investigations concluded that Machining performance was enhanced in micro-EDM when micro hole was generated on Ti-6AI-4V alloy by using Boron carbide as an additive in deionized water [12]. It has been seen that water as Dielectric possess better results in high speed Electro discharge machining [13]. During EDM, Ti alloys possess low material removal rate thus consuming lot of time due to long machining duration. Graphite powder with kerosene dielectric liquid is used as dielectric in EDM machining and various chemical, physical and mechanical properties like MRR, surface roughness is investigated and concluded that MRR is improved in Ra and Rz by adding graphite powder into the kerosene dielectric (GPMKD) during machine process. It is also seen that there are distributed surface peaks and valleys over the machined surfaces. The discharge energy of the spark is spread over a large area of surface thus producing peaks with short and round tips. The EDM performance of Ti-6Ai-4v alloy is also compared with the AISI1040 steel using GPMKD [14-16]. To increase the material removal rate in EDM machining, Jatropha biodiesel is used and it has found that the jatropha Biodiesel influenced the tremendous increase in MRR upto 38% and thus leading to the effective oil to use in Electric Discharge Machining. It is also seen that jatrophabiodiesel has also excellent effect on current and gap voltage as it supports improved surface finish and higher surface hardness. Thus above results make it feasible to be used as dielectric in EDM machining techniques [17]. The EDM machining of titanium alloy with several electrode material like graphite, electrolyte copper and aluminum and process parameters to know influence of EDM parameters on different aspects of the surface integrity of TI-6AI-4V.Scanning electron microscopy, x-ray diffraction and hardness analysis are also included in the research and thus found that value of SR ,electrode wear ,MMR have a tendency of increasing with increase in current density and pulse duration and SR is decreased by the long pulse duration such as 200MS. When Ti-24-C15 carbide is formed, the surface hardness increases and cracks are marked in solidified layer [18]. To find machining efficiency along with additive power mixed in dielectric fluid and copper electrode is used cryogenically to identify the effect of input parameters. Duty cycle, pulse on time, peak current gap voltage polarity, retract distance and concentration of fine graphite powder on machining efficiency. Tool wear retract wear ratio are the factors used to find machining efficiency. The analysis of variance is used to indicate the level significance of two parameters TWR and WR. The required input conditions were verified by conducting confirmation experiments[19]. The copper tungsten is utilized as electrode. The investigators changed peak current, pulse on time and pulse off time to measure the corresponding values of surface roughness (SR) respectively and used mathematical graphs to elaborate the correlation between peak current and surface roughness. This experiment was conducted according to Design of experiment (DOE) method and response surface methodology (RSM) techniques and analysis of variance (ANOVA) is used to carry out the adequacy of proposed methods. This concluded that peak current and pulse on time has positive influence on surface roughness. The excellent surface finish is also investigated at short pulse on time. The finest machining conditions in favor of surface roughness are estimated and verified with proposed optimized results thus leads to required surface roughness and economical industrial machining by optimizing the input parameters of EDM machining [20,21]. With the help of multiple performance characteristics which is based in the orthogonal array with grey relational analysis, a technique has been studied for optimization of abrasive mixed electrical discharge machining process. Concentration of silicon abrasive powder in dielectric fluid, peak current and duty factor have studied and influence of powder based dielectric having silicon powder suspended in kerosene dielectric is observed on material removal rate and surface roughness. It is seen that they possess better MRR and SR [22-24]. As we now that electro-discharge machining (EDM) have high machining cost as it takes longer machining time, we can increase efficiency by using powder-mixed dielectric fluid (PMEDM). To improve machined part surface finish, material removal rate andreduce tool wear rate, It works at low pulse energy and distribute the powder in machining area gradually. The analysis of powder mixed EDM has also done subsequently. Number of experiments to be conducted is based on Taguchi orthogonal array with three level and two factors [25]. Titanium powder based dielectric fluid possesses positive influence on EDM process as it tends to increase the MRR without affecting the TWR [26]. The very low material removal rate (MRR) of the Ti alloys the EDM process causes prohibitively long machining durations. Kerosene-graphite mixture (GPMKD) as dielectric for EDM machining has a commendable influence on various EDM performances as improved MRR , Ra and Rz(DIN) surface roughness and decreases the RW.3D topographic views of the machined work-piece surfaces exhibits uniformly distributed surface valleys and peaks over the surface. The surface also possess peaks with short and round tops as the discharge energy of a spark was distributed over a large area at the machining gap in the experimentation. This increases the chances to use Graphite based powder-dielectrics for EDM processes in Industry[27]. It is also observed that water with urea solution as dielectric possesses improved machining along with improved characteristics [28].

In the electric discharge machining process of Ti-6AL-4V using relational and Taguchi method, various characteristics like material removal rate, surface roughness, and discharge current, open voltage and duty parameters were observed. After the investigation according to the grey relational analysis of performance characteristics, it revealed the improved electrode wear ratio, material removal rate and surface roughness as 15%, 12% and 19% respectively [29,30].It has also seen that with Taguchi method, quality of hole on titanium alloy is increased [31,32]. EDM was opted to investigate the characteristics like material removing rate, tool wear ratio, while considering the performance method as crack formation, white layer thickness for Ti-6AL-4V. The investigators used EDS and XRD analyzer to know the possibility of forming different chemical elements on work surface and suggested to increase the pulse energy to improve the material removal efficiency for thickness and micro hardness layer standard [33]. When Ti-6Al-4V and Ti-6AL-7NB high strength alloys, in form of 10 mm diameter ball, were tested in tribotester according to ISO [34,35], it is concluded that the both alloys have the same wear behavior and friction although they have different composition and structure. This investigation also concluded that large friction is occurred due to fluctuation and high wear rate produced due to higher siding speed [36]. Researchers also clarified the use of Ti-Ta-Zr-Nb alloy for biomedical implants [37]. The effects of peak current, pulse on time and pulse off time in electric discharge machining (EDM) performance were also examined on titanium alloy Ti6AI4V with optimized model. The literature survey on application of EDM and WEDM on titanium materials, application of products produced by EDM and WEDM and utilization of tools and techniques for correlating experimental results was carried out. And found that some of the techniques for tools have t utilized for experimental results [38]. Temperature measurement for Ti-6Ai-4v has also been made and various thermal and electrical properties are studied and it is found that with the increment of duty factor, the internal temperature of work piece also increases that leads to poor tooling and machining [39]. The peak current IP, pulse off time, pulse on time, servo reference voltage on MRR, surface roughness are also examined and analysis of variance (ANOVA) is implemented to investigate the WEDM parameters and found that Pulse on time was the effective factors whereas servo voltage and pulse off time are less effective parameter thus to achieve high MRR for surface finish [40] In Grey relational theory based parameter optimization in electro discharge machining (EDM) of Ti-6A1-4V alloy, surface roughness, material removal rate and electrode wear rate were optimized and thus it is seen that copper possess optimum performance as per as higher MRR and lower EWR are concerned [41]. Surface topology also plays a vital important role in several implants of Titanium alloy. An admiring performance of electric discharge machining for surface modification, has also been observed with respect to biocompatibility and surface quality of biomaterial [42,43].In die-sinking Electric discharge machining of reaction bonded silicon carbide (SiSiC), material removal rate and electrode wear were studied and also resulted influence of Pulse time, duty cycle, open current voltage and dielectric flushing pressure according to design of experiments (DOE) is observed. Although, MRR and EW were rejected after the first model but EW has found advanced results whereas pulse time showed opposite response [44]. EDM has resulted in the mirror-like surface of AISI-D2 die steel using carbon nanotubes, thus influencing that CNTs are an effective approach to gain surface finish. CNTs also results in improved SR and MRR of material [45]. Wc-Co coated grades are given more preference in a most of application where wear resistance is important. These applications are generally found in drilling, milling, turning of steel, alloys and ceramics with crater wear resistance offered. Because of the hardness of Wc-Co, it provides abrasive wear resistance that consequently reduces down the flank wear, and brings improvement of edge toughness in interrupted cuts. However to avail this, surfaces modification generally required to stand against wear, crater formation etc. Here the surface modification of Wc-Co work-piece is done by electric Discharge Coating process with help of SiC-Cu green compact tool electrode. The hard layers created on work piece surface by using powder metallurgy tool electrode. In this material transfer takes place to create hard layer on surface. The current study has been carried out to find out the effect of input parameters such as peak current, pulse on time etc. on process performance parameters[46,47]. Micro hardness effect by current, powder and interaction between work-piece and electrode. Copper electrode was best for EN31 and H11 die steel, and tungsten-copper electrode was better for HcHcr steel to fulfill higher micro hardness. Samples were checked for x-rays diffraction followed by microscope. This experiment showed that material transfer from the electrode either in free form or in compound form. For maximizing the micro hardness of the machined surface by using perfect parametric setting. [48]. When Cupper Titanium (Cu-Ti) is used as electrode for copper electrode during electric discharge machining of Supreni-800, was found with the Taguchi's experimental design and analysis of variance (ANOVA) that Cu-Ti electrode influenced to higher MRR and WR thus resulting in better machinability of Superni-800 [49]. Grey-Taguchi'sProcess also optimizes the time span and lesser pulse-on Time for machining of Ti-alloys [50]. Cryogenic cooling is a very sustainable process because of its environment friendly, and economically and societal-beneficial nature. Thus to improve functional performance, surface hardness; wear resistance, corrosion resistance and life of implant materials, Cryogenic machining exhibits successive impact on material as it enhanced the surface and sub-surface integrity [51]

Society, environment and economy (people, planet, and profit) are the three main pillars of sustainability. Energy and resource efficiency are the key drivers that sustain these pillars and also help to keep clean and green environment that incorporates effective waste reduction and management, finally cost-effective production. The sustainable manufacturing implies technologies or different advanced techniques whose targets are these key drivers during the manufacturing of product. In the machining of titanium and its alloys, the effort and cost are involved, that is why there is a significant scope for improved sustainability. Titanium andits alloys are used for the aerospace, medical andgeneral industry. As sustainable machining of titanium and its alloys is concerned, various methodologies and techniques are being adopted to machine Titanium alloy with economic and environment friendly way and also to improve the machinability of titanium and itsalloys. [52] The disease named as Parkinson' is an idiopathic disorder of central nervous system shows symptoms like muscular rigidity, slow and decreased movement. For the rehabilitation of patients suffering from this disease, It requires special care, especially for the case where the patient status is not good. This report presents care of patient suffering from this disease who was completely rehabilitated in three appointments using the special techniques and treatment. [53] Titanium alloy is giving more preference for the long term hard body tissue replacements such as hip and knee joints among the various metallic implants materials. It has good mechanical, strong anticorrosion and superior biological properties. Apart from the appropriate implant material, its surface topology also plays a very crucial role in the success of any surgery. For the promotion of Osseo integration, the surface topology is considered to be important factor. The research article mainly pays its attention to the surface modification of Ti-based alloys with the help of electric discharge machining process. Basically the Electric discharge machining process is considered to be the one of important non-traditional manufacturing process. It has applications in almost all areas of manufacturing industries rather than only machining and surface modification of implants. The area which is taken into consideration for this research review has orthopedics applications. It also elaborated the advancements in biocompatibility and surface quality of biomaterials. [54,55]. The need for miniaturized components is increasing, particularly from the biomedical and aerospace industry. Because of this demand, it becomes a field of research towards the micro-manufacturing of biomedical and aerospace components. Titanium based alloys are normally used for these applications because of their superior results in compatibility, high strength to wear ratio and span time [56]. The basic performance parameters of typical micromachining such as flank wear progression, surface roughness and side burrs are presented and analyzed through analysis of variance in order to know the key process parameters. It was found that micromachining is of two types that is micromachining with undeformed chip thickness below the tool edge radius and micromachining keeping the undeformed chip thickness above the tool edge radius. It has been observed that undeformed chip thickness above edge radius, surface roughness (83%), burr width (80%) and tool wear (41%). With micromachining below edge radius there is 17% tool wear, 53% surface roughness and 52% burr width. The result indicates consideration the tool edge radius in micromachining. [57]

The microstructure of Ti-6Al-4Nb and Ti-10Al-4Nb alloys processed using plane strain compression test was investigated in the phase region (10500C). Plane strain compression test (PSCT) was performed with strain rate of 0.1 S-1 to yield about 70% of deformation. For precise phase and texture characterization of these alloys, high-resolution EBSD was successfully used. The microstructure of homogenized samples consisted of mainly phase and thin phase plates between phase grains. Dynamic recrystallization takes place in both alloys [58]. It is also seen in the investigation done on vitro and vivo based behaviors of implant materials that the materials don't dislocate themselves during the bone growth. It has also seen that Ti-6Al-4V possess potential capability and stability during the bone growth [59,60]. Although materials and ceramics cannot completely exhibit biocompatibility parameters for diseased or fractured bone, bioactive coatings plays an important role in maintaining the supportive biocompatibility between metal and bone tissues [61]. In some EDM processes, carbon enriched surface layer on Ti-6Al-4V has also formed for the proper biocompatibility and improved osteointegration [62-65].It is observed that the recent biomedical implants accepting the plate removal after a time period influencing the palpability and visibility [66-70].Recent researches are being carried out to visualize EDM of non-conductive materials. Scientists and researchers are continuously searching more adoptable methods and materials to implement on the biomaterials and thus to increase biocompatibility and vice versa [71,72].

Conclusions

The EDM has potential in treatment and modification of Titanium alloy and other metallic materials used for biomedical applications. In comparison to the several existing techniques such as CVD, PVD and iodization, EDM shows better potential for surface treatment of metallic implants. EDM has tremendous results for Material Removal Rate, Surface Roughness and other parameters.The only disadvantage is that the fatigue performance of the highly rough EDM sample is low, which can be further improved by surface treatment method or by the reduction of recast layer by shot blasting, CM, SP and so on. However, the use of EDM process in the medical era is still in its early life. The rapidly growing field of bio manufacturing faces significant challenges and opportunities. The role of EDM process for surface modification of biomaterials is still at the experimental stage. Despite this, there is a gap and the urgent need to study the effect of various input-independent parameters of EDM on the formation of biocompatible surface. It is also necessary to find more sustainable alloy and materials for the utilization in biomedical implants. Yet, many more issues need to be addressed before the method can be embraced by the biomedical industry.

Future Scope

It is clear from the above literature review that Titanium based alloys are most prominent biomaterials for the biomedical implants. Although Ti-6A1-4V is most accepted alloy for biomedical implants, it is tended to be replaced after time period of fifteen years or more. Thus, Modern Civilization needs more advanced and durable bio alloys for increased time limit and Human-friendly approach.

Acknowledgement

The author Vijay Kumar would like to acknowledge Inder Kumar Gujral Punjab Technical University,Kapurthala,Punjab, India,Medical Officer, IVY Hospital, Amritsar, Punjab, India and Department of Mechanical Engg. Beant College of Engineering & Technology, Gurdaspur, Punjab, India for providing the support and facilities tocarry out this research work.

References

1. X. Wang, S.Xu, S.Zhou et el al. (2016) 'Topological design and additive manufacturing of porous materials of bone sacfolds and orthopedical implants: a review," Biomaterials, Vol 83, no. 6, pp. 127-141.
2. F.Gayner Evans (1976) The mechanical properties of bone. pp. 1-12, ANAT. REC., 185, Published online: https://pdfs.semanticscholar.org/0223/825eb119165.
3. M. J. Mirzaali, J. J. Schwiedrzik, S. Thaiwichai et al. (2016) "Mechanical properties of cortical bone and their relationships with age, gender, composition and microindentation properties in the elderly," Bone, vol. 93, pp. 196–211.
4. F. Libonati and L. Vergani (2016) "Understanding the structure-property relationship in cortical bone to design a biomimetic composite," Composite Structures, vol. 139, pp. 188–198.
5. M. Saini, Y. Singh, P. Arora, V. Arora, and K. Jain (2015) "Implant biomaterials: A comprehensive review", World Journal of Clinical Cases, 2015 Jan 16; 3(1) pp. 52–57; doi: 10.12998/wjcc.v3.i1.
6. J.-Y. Rho, L. Kuhn-Spearing, and P. Zioupos (1998) "Mechanical properties and the hierarchical structure of bone," Medical Engineering & Physics, vol. 20, no. 2, pp. 92–102.
7. Cranin AN, Silverbrand H, Sher J, Satler N. (1982) The requirements and clinical performance of dental implants. Biocompatibility of dental materials. 1982;4. pp.92–102.
8. Tschernitschek H, Borchers L, Geurtsen W. (2005) Nonalloyed titanium as a bioinert metal--a review. Quintessence Int. 2005;36. pp.523–530.
9. Cristiano C. Gomes, Leonardo M. Moreira, Vanessa J.S.V. Santos, Alfeu S. Ramos, Juliana P. Lyon, Cristina P. Soares, Fabio V. Santos (2011) "Assessment of the genetic risks of a metallic alloy used in medical implants"; Genet Mol Biol. 2011 Jan-Mar; 34(1) pp. 116–121. Published online 2011 Mar 1. doi: 10.1590/S1415-47572010005000118 PMCID: PMC3085356.
10. PetrHarcubaa, Lucie Bacakovab, Josef Straskya, MarketaBacakovab, Katarina Novotnab, Milos Janeceka. (2012) Surface treatment by electric discharge machining of Ti–6Al–4V alloy for potential application in orthopaedics. journal of the mechanical behavior of biomedical materials, Vol. 7, pp. 96–105.
11. B. Purna Chandra Sekhar, S. Radhika, D. Sameer Kumar (2015) Powder mixed Dielectric in EDM – An Overview; International Journal of Research; p-ISSN: 2348-6848.
12. G. Kibria, B. R. Sarkar, B. B. Pradhan& B. Bhattacharyya (2010) Comparative study of different dielectrics for micro-EDM performance during microhole machining of Ti-6Al-4V alloy. Journal of Int J AdvManufTechnol, Vol. 48, pp. 557–570.
13. ZhaojunKoua, Fuzhu Han (2018) On sustainable manufacturing titanium alloy by high-speed EDM milling with moving electric arcs while using water-based dielectric; Journal of Cleaner Production, Published online doi: 10.1016/j.jclepro.2018.04.072.
14. 14.EMRE UNSES and COGUN CAN. (2015) Improvement of Electric Discharge Machining (EDM) Performance of Ti-6Al-4V Alloy with Added Graphite Powder to Dielectric. Journal of Mechanical Engineering Vol. 61, no. 6, pp. 409-418.
15. Muhammad PervejJahan, MustafizurRahman, Yoke San wong (2011) Study on nano powder mixed sinking and milling micro-EDM of WC; The international journal of advanced manufacturing technology; springer. Volume 53, Issue 1–4, pp. 167–180.
16. Prihandana, G.S., Mahardika, M., Hamdi, M. et al. Int J AdvManufTechnol (2011) Accuracy improvement in nanographite powder-suspended dielectric fluid for micro-electrical discharge machining processes; 56, pp.143-149. https://doi.org/10.1007/s00170-011-3152-6.
17. Janak B. Valaki, Pravin P. Rathod and C.D. Sankhavara (2016) Investigations on technical feasibility of Jatrophacurcas oil based bio dielectric fluid for sustainable electric discharge machining (EDM). Journal of Manufacturing Processes, Vol. 22, pp. 151–160.

18. Hascalık, Ahmet and CaydasUlas (2007) Electrical discharge machining of titanium alloy (Ti 6Al 4V). Journal of Science Direct, Applied Surface Science, Vol. 253, Issue 22, pp. 9007-9016.
19. Anil Kumar, SachinMaheshwari, ChitraSharma and Naveen Beri (2012) Machining Efficiency Evaluation of Cryogenically Treated Copper Electrode in Additive Mixed EDM. Journal of Taylor & Francis, Materials and Manufacturing Processes, Vol. 27, pp. 1051–1058.
20. M.M. Rahman, Md. AshikurRahman Khan, K. Kadirgama, M.A. Maleque and Rosli A. Bakar (2011) Parametric Optimization in EDM of Ti-6Al-4V using Copper Tungsten Electrode and Positive Polarity: A Statistical Approach. Journal of Mathematical Methods and Techniques in Engineering and Environmental Science, Proceedings, Vol. 13, pp.1-7.
21. B. Kishana , B.SudheerPremkumara , S. Gajanana, K. Buchaiahc, M.A.Gaffara (2018) Development of Mathematical Model for Metal Removal Rate on EDM using Copper & Brass Electrodes; Materials Today: Proceedings 5, Volume 5, Issue 2, Part 1, pp. 4345-4352.
22. Anil Kumar, S. Maheshwari, C. Sharma & Naveen Beri. (2010) A Study of Multi objective Parametric Optimization of Silicon Abrasive Mixed Electrical Discharge Machining of Tool Steel. Journal of Materials and Manufacturing Processes, Vol. 25, pp. 1041–1047.
23. GurpreetSingh, GurmailSingh, KamaljitSingh, AmitSingla (2017) Experimental studies on material removal rate, tool wear rate and surface properties of machined surface by powder mixed electric discharge machining; Materials Today proceedings, Volume 4, Issue 2, Part A, pp. 1065-1073.
24. F. Klockea, M. Mohammadnejad, M. Holsten , L. Ehle, M. Zeis, A. Klink (2018) A comparative study of polarity-related effects in single discharge EDM of titanium and iron alloys; Procedia CIRP, Volume 68, pp. 52-57.
25. M. A. Razak, A. M. Abdul-Rani and A. M. Nanimina (2015) Improving EDM Efficiency with Silicon Carbide Powder-Mixed Dielectric Fluid. International Journal of Materials, Mechanics and Manufacturing, Vol. 3, Issue -1, pp. 44-43.
26. BanhTien Long, Ngo Cuong and Nguyen (2014) Effects of Titanium Powder Concentrations during EDM Machining Efficiency of Steel SKD-61 Using Copper Electrode. Journal of International Journal of Advance Foundation And Research In Science & Engineering (IJAFRSE) Volume 1, Issue 7, pp. 9-19.
27. EmreUnses and Can Cogun (2015) Improvement of Electric Discharge Machining (EDM)Performance of Ti-6Al-4V Alloy with Added Graphite Powder to Dielectric. Journal of Mechanical Engineering, Vol. 61, Issue-6, pp. 409-418.
28. BiingHwa Yan, Hsien Chung Tsai, Fuang Yuan Huang (2004) The effect in EDM of a dielectric of a urea solution in water on modifying the surface of titanium; International Journal of Machine Tools and Manufacture, pp.194-200. https://doi.org/10.1016/j.ijmachtools.2004.07.006.
29. J. Y. Kao & C. C. Tsao& S. S. Wang & C. Y. Hsu. (2010) Optimization of the EDM parameters on machining Ti–6Al–4V with multiple quality characteristics. Journal of Int J AdvManufTechnol, Vol. 47, pp. 395–402.
30. J. Prasanna,m L. Karunamoorthy, M. Venkat Raman, SaiPrashanth, D. Raj Chordia (2014) Optimization of process parameters of small hole dry drilling in Ti–6Al–4V using Taguchi and grey relational analysis; Measurement Measurement; 48; pp.346-354.
31. K.Nagendra Prasad , D.johnBasha , K.C.Varaprasad (2017) Experimental Investigation and Analysis of Process Parameters in Abrasive Jet Machining of Ti-6Al-4V alloy using Taguchi Method; Materials Today: Volume 4, Issue 10, pp.10894-10903.
32. W.MersniM.Boujelbene S. BenSalem A-S.Alghamdi (2018) Optimization of the surface roughness in ball end milling of titanium alloy Ti-6Al-4V using the Taguchi Method; Procedia Manufacturing Volume 20, 2018, pp. 271-276.
33. B. Jabbaripour, M. H. Sadeghi, Sh. Faridvand and M. R. Shabgard. (2012) Investigating the effects of EDM parameters on surface integrity, MRR and TWR in machining of Ti–6Al–4V. Journal of Machining Science and Technology, Vol. 16, pp. 419–444.
34. A.A. Bakathir, M.V. Margasahayam, M.I. Al-Ismaily (2008) Removal of bone plates in patients with maxillofacial trauma: a retrospective study, Oral Surg Oral Med Oral Pathol Oral RadiolEndod, 105, pp. e32-e37.
35. Li, Xiaopeng& Liu, Zk&Ji, Renjie. (2012). A New Method for Electrical Discharge Machining of Non-Conductive Engineering Ceramics. 10.2991/emeit.2012.280.
36. Mamoun Fellah, Mohamed Labaz, Omar Assala, Leila Dekhil, AhlemTaleb, HaddaRezag, and Alain Iost. (2014) Tribological behavior of Ti-6Al-4V and Ti-6Al-7Nb Alloys for Total Hip Prosthesis. Journal of Advances in Tribology, Article ID 451387, pp. 1-13.
37. SertanOzan, Jixing Lin, Yuncang Li, Cuie Wen (2017) New Ti-Ta-Zr-Nb alloys with ultrahigh strength and elastic strain for potential orthopedic implant applications; Journal of the Mechanical Behavior of Biomedical Materials,Volume 75, pp.119-127.
38. M. Manjaiah, S. Narendranath and S. Basavarajappa (2014) A review on machining of titanium based alloys using EDM and WEDM. Journal of Rev. Adv. Mater. Sci. Vol. 36, pp. 89-111.
39. Peter Fondaa, ZhigangWanga, Kazuo Yamazakia and Yuji Akutsub (2008) A fundamental study on Ti–6Al–4V's thermal and electrical properties and their relation to EDM productivity. journal of materials processing technology Vol. 202, pp. 583–589.
40. A.V.S Ram Parsad ,KoonaRamji , G.L.Datta (2014) An Experimental study of wire EDM on Ti-6Al-4V Alloy. Journal of ScienceDirect, Procedia Materials Science Vol. 5, pp.2567-2576.

41. MitaliS.Mhatre, SagarU.Sapkal and RajuS.Pawadeb (2014) Electro Discharge Machining Characteristics of Ti-6Al-4V Alloy: A Grey Relational Optimization. Journal of Science Direct, Procedia Materials Science, Vol. 5 , pp.2567-2576.
42. ChanderPrakash, Harmesh K Kansal, BS Pabla, SanjeevPuri and AdityaAggarwal (2015) Electric discharge machining – A potential choice for surface modification of metallic implants for orthopedic applications. Journal of Engineering Manufacture, pp. 1–23.
43. Josef Strasky, Milos Janecek, PetrHarcuba, Michal Bukovina, Lothar Wagner (2011) The effect of microstructure on fatigue performance of Ti–6Al–4V alloy after EDM surface treatment for application in orthopaedics; Journal of the Mechanical Behavior of Biomedical Materials,Volume 4, Issue 8, pp.1955-1962.
44. C.J. Luis, I. Puertas and G. Villa (2005) Material removal rate and electrode wear study on the EDM of silicon carbide. Journal of Materials Processing Technology, Vol. 164, pp. 889–896.
45. Harmesh Kumar. (2015) Development of mirror like surface characteristics using nano
46. powder mixed electric discharge machining (NPMEDM) .The International Journal of Advanced Manufacturing Technology, Vol.76, Issue-1, pp. 105-113.
47. Deepak Kumar, Ketan Mittal, Suresh Kataria, Sunil Kadiyan and Seeone Sharma (2013) Experimental Investigation on Surface Modification of Wc-Co by Electric Discharge Coating Process Using Sic/Cu Green Compact Tool-Electrode. Journal of International Journal of Research in Mechanical Engineering &Technology,Vol. 3. Issue-2. pp. 274-278.
48. Purna, B &Sajja, Radhika&Devarakonda, Sameer Kumar. (2015). Powder Mixed Dielectric in EDM –An overview. International Journal of research. Volume 2, Issue-2, ISSN 2348-6848,pp.720-726.
49. Ajay Batish, AnirbanBhattacharya, V. K. Singlaand Gurmail Singh (2012) Study of Material Transfer Mechanism in Die Steels Using Powder Mixed Electric Discharge Machining. Journal of Materials and Manufacturing Processes, Vol. 27, Issue-4, pp. 449-456.
50. Vijay Kumar Bhanot, Naveen Beri and Anil Kumar (2014) Machinability assessment of Superni-800 during EDM with powder metallurgy processed Cu-Ti electrode using the Taguchi method. Proceedings of AIMTDR 2014-IIT Guwahati, 5th International & 26th All India Manufacturing Technology, Design and Research Conference, pp. 602/1- 602/6.
51. ManishaPriyadarshinia, Kamal Pal Grey (2015) Taguchi based optimization of EDM process for titanium alloy, 4th International Conference on Materials Processing and Characterization, Materials Today: Proceedings Volume 2, Issues 4-5, pp. 2472-2481.
52. I.S. Jawahira, D.A. Puleob and J. Schoopa (2016) Cryogenic machining of biomedical implant materials for improved functional performance, life and sustainability. Journal of Science Direct, Conference on High Performance Cutting, Procedia CIRP-46, pp. 7-14.
52. Kapil Gupta and Rudolph F Laubscher (2016) Sustainable machining of titanium alloys: A critical review, Journal of Engineering Manufacture, pp. 1-18.
53. Yashpal Singh, Monika Saini and NehaGarg (2013) Oral rehabilitation of a Parkinson's patient: A case report. World Journal of Clinical Cases (WJCC), Vol. 16, Issue-1, pp. 67-70.
54. ChanderPrakash, Harmesh K Kansal, BS Pabla, SanjeevPuri and AdityaAggarwal (2015) Electric discharge machining – A potential choice for surface modification of metallic implants for orthopedic applications: A review. Journal of Engineering Manufacture, pp. 1–23.
55. Chaturvedi T P (2009) An overview of the corrosion aspect of dental implants (titanium and its alloys); Indian Journal of Dental Research. Volume 20, Issue-1, pp. 91-98.
56. Mohammad Antarab, DimitriosChantzisa, SundarMarimuthuac, Philip Hayward (2016) High Speed EDM and Laser Drilling of Aerospace Alloys; Procedia CIRP, Volume 42, 2016, pp. 526-531.
57. Syed H Imran Jaffery,Mushtaq Khan, Liaqat Ali and Paul T Mativenga (2015) Statistical analysis of process parameters in micromachining of Ti-6Al-4V alloy. Journal of Engineering Manufacture, pp. 1-18.
58. A. Jastrzebska, K.S.Suresh, T.Kitashima, Y.Yamabe-Mitari, Z.Pakiela (2016) An EBSD investigation of Ti-6Al-4Nb and Ti-10Al-4Nb alloys processed by plane strain compression test. Proceedings of the 13th World Conference on Titanium,The Minerals, Metals & Materials Society, pp. 282-284.
59. Li, Guoyuan& Wang, Lei & Pan, Wei & Yang, Fei& Jiang, Wenbo& Wu, Xianbo& Kong, Xiangdong& Dai, Kerong&Hao, Yongqiang. (2016). In vitro and in vivo study of additive manufactured porous Ti6Al4V scaffolds for repairing bone defects. Scientific Reports. 6. 34072. 10. pp.1038/srep34072.
60. Ying-Sui Suna , Chi-Ya Huang, Chiang-Sang Chenc, Jean-Heng Chang, Wen-Tao Houe , Shu-Jun Lie, Yu-Lin Haoe, Her-Hsiung Huang (2018) Bone cell responses to a low elastic modulus titanium alloy surface immobilized with the natural cross-linker genipin. Published online https://doi.org/10.1016/j.surfcoat.2018.03.069.
61. Micheal N. Helmus, Donald F. Gibbons, David Cebon (2018) Biocompatibility: meeting a key functional requirement of next generation medical devices; society of toxicological pathology; DOI:10.pp.1177/0192623307310949
62. J. Strasky, M. Janecek, P. Harcuba (2011) Electric discharge machining of Ti-6Al-4V alloy for biomedical use; pp.127-131, ISBN: 978-80-7378-186-6 copyright – MATFYZPRESS
63. P.S. NooriBanu, S. Devaki Rani (2018) Artificial neural network based optimization of prerequisite properties for the design of biocompatible titanium alloys; Computational Materials Science 149, pp. 259–266.

64. Muhanad M. Hatamleha, XiaohongWub, Ahmad Alnazzawi, Jason Watsond, David Watts (2018) Surface characteristics and biocompatibility of cranioplasty titanium implants following different surface treatments. Dental Materials,Volume 34, Issue 4, pp. 676-683.
65. JopP.Verweij, GertJ.M.Hassing, MartaFiocco, Pascal N.W.J.Houppermans, J.P. RichardvanMerkesteyn (2018) Removal of osteosynthesis material because of symptoms after Le Fort I osteotomy: A retrospective study of 158 patients; Journal of Cranio-Maxillofacial Surgery,Volume 44, Issue 12, pp. 1909-1912.
66. J.S. Orringer, V. Barcelona, S.R. Buchman (1998) Reasons for removal of rigid internal fixation devices in craniofacial surgery, J CraniofacSurg, 9, pp. 40-44.
67. Y. Kubota, T. Kuroki, S. Akita, T. Koizumi, M. Hasegawa, N. Rikihisa (2012) Association between plate location and plate removal following facial fracture repair. JPRAS International Journal of Surgical Reconstruction, Volume 65, Issue 3, pp. 372-378.
68. D.Y. Nagase, D.J. Courtemanche, D.A. Peters (2005) Plate removal in traumatic facial fractures, Annals of Plastic Surgery, Volume 55, Number 6, pp. 608-611.
69. G. Chaushu, Y. Manor, Y. Shoshani, S. Taicher (2000) Risk factors contributing to symptomatic plate removal in maxillofacial trauma patients, American Association of Oral and Maxillofocial Surgeons, PlastReconstrSurg, 57, pp. 679-682.
70. AbdusSabur, Mohammad Yeakub Ali, Md. Abdul Maleque, Ahsan Ali Khan, (2013) Investigation of Material Removal Characteristics in EDM of Nonconductive ZrO2 Ceramic, Procedia Engineering, Volume 56, pp. 696-701, ISSN 1877-7058.
71. Banu, A., Ali, M.Y. &Rahman, M.A. Int J AdvManufTechnol (2014) Micro-electro discharge machining of non-conductive zirconia ceramic: investigation of MRR and recast layer hardness, Volume 75, Issue 1-4, pp. 257-267.
72. Nikita Agarwal, SiddharthShukla, VarshitAgarwal, Swati Agarwal and UtkarshMaurya (2015) Investigation of Material Removal Method in EDM for Non-Conductive Materials, European Journal of Advances in Engineering and Technology, 2015, 2(4), ISSN: 2394 - 658X, pp. 11-13.